VESTIBULAR PROBLEMS IN RELATION TO SPACE TRAVEL*

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Among the stresses with which man must contend in the exploration of space are those which have their affect on the semicircular canals and otolith organs as a result of exposure to unusual gravitoinertial force environments. These unusual force environments will have a changing pattern in the future, depending on change in launch vehicle, spacecraft, and mission, but today we are interested in the effects of high G loading, weightlessness, and "artificial gravity."

In any consideration of the effects of different force environments on the vestibular organs it is essential to consider the effects on the semicircular canals and otolith organs individually and collectively. The canals are stimulated ordinarily by inertial forces resulting from angular and gyroscopic accelerations. These accelerations are generated by active or passive movements of the head (body) or by both acting simultaneously. Active bodily movements involving rotation of the head stimulate one or more of the three pairs of canals regardless of body position. The orientation or changing orientation of the canals with reference to the force environment is, however, important partly because of individual differences in response to stimulation of different pairs of canals and partly because of other factors which are changing coincidentally.

The sensory receptors in the otolith organs are stimulated by gravity or, more particularly, by changes in position of the head in a central field force. They are also stimulated by gravitoinertial forces representing the vector sum of gravity and the linear or Coriolis forces generated by bodily movements. In man it is impossible to stimulate the otolith organs without also stimulating nonotolith gravireceptors. This greatly increases the difficulty of identifying the unique role of these organs.

Great emphasis has been placed on the interrelationships of canals and otoliths. Although certain relationships have been demonstrated they are probably less important than those between either canals and vision or otoliths and vision.

It is known from long experience and laboratory experiments that exposure to unusual force environments even well within the physiological range may cause illusions and motion sickness. It is also known that normal persons not only vary greatly in their susceptibility to symptoms under these circumstances but also that a given person may be more affected in one type of force environment than in another. Attempts (1-3) to elucidate the factors which are responsible for inter- and intraindividual differences have not been completely successful but have pointed up the almost incredible complexity of the factors involved. The only persons who are insusceptible are those who have suffered a loss of function of the canals and otoliths. Thus the assessment of the function of these organs is a very important point of departure in dealing either with the analysis of etiological factors or the symptomatology and effectiveness of countermeasures. Assessment of otolith function is in a far less satisfactory state than that of canal function, and assessments of combined functions may also prove to have validity.

The above remarks are intended to emphasize the need for background information without which one cannot predict satisfactorily the disturbing effects of exposure to unusual force environments such as will be encountered in space flight.

HIGH G FORCES

During launch, re-entry, and on impact the astronaut is subjected to high level linear G forces. The fact that following simulation trials on a centrifuge and exposure to high G forces on other occasions, some subjects manifested vertigo and ataxia suggests that these levels of force might be injurious. At present two lines of investigation are being pursued: first, a follow-up study of persons with a history of exposure to high level G force and second, a systematic investigation involving the exposure of primates to graded levels of gravitoinertial force followed by clinical pathological correlations. Herbert Pollack, who is conducting the follow-up study, has not reached a point in his investigation where a report can be made. The studies on chimpanzees now being conducted at Holloman Air Force Base are likewise incomplete. Recently, Spoendlin, Schuknecht, and Graybiel (4) have reported an experiment in which eleven squirrel monkeys were exposed to forces of either 10.92

or 5.43 G units for periods of one to ten minutes. For periods of minutes to hours following exposure several animals were ataxic. Pathological studies were limited to the macula. The ultrastructure of this organ as revealed by electronmicroscopy failed to show any significant changes when compared with that of normal controls. This raised two questions; namely, at what level of force will the first indications of injury appear and was the ataxia manifested by the monkeys caused by injury to the canals. More studies along these lines are needed.

WEIGHTLESSNESS

The individuality of the vestibular organs is beautifully revealed under conditions of weightlessness in that there is deafferentation (suppression) of the otolith organs whereas the canals are stimulated the same or very nearly the same as under terrestrial conditions by the inertial forces generated with the rotary motions of the head.

Not only the otolith apparatus but all receptors directly or indirectly stimulated by gravity are also affected in weightlessness.* These two categories of receptors are affected quite differently, however, by man's activities in a weightless spacecraft. Stimulation of the otoliths could occur only in consequence of bodily movements involving the head. On the other hand, touch, superficial and deep pressure, kinesthetic and other somesthetic gravireceptors could be stimulated by deformations or movements of parts of the body while the head is motionless. Some of these so somesthetic inputs would provide cues which would accord with the visual upright

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*Weightlessness is arbitrarily defined as any subgravity level below 10^{-5} G units.

whereas even if the otoliths were stimulated by head movements, the force vector would not point, with rare exception, in the direction of the visual upright. Moreover, slight negative (headward) accelerations would tend to cause the "inversion illusion."

In the light of these considerations, it is worthwhile to review very briefly the observations which have been made when subjects have been exposed to weightlessness in parabolic (5-12) and orbital flight (13-18).

The findings in parabolic flight must be interpreted with caution inasmuch as the weightless phase not only is brief but is preceded and followed by a maneuver which exposes the subjects to moderate G loading, and, in a typical flight, these transitions occur repeatedly. On the other hand, some advantage is gained by the fact that these interpretations are based on relatively large numbers of subjects with varying susceptibility to airsickness who have been tested under restrained and "free floating" conditions. Although more than half of the subjects who have participated in parabolic flight experienced definite symptoms of airsickness, only a few pilots without a history of airsickness were found to be susceptible. In general, subjects when secured in a seat were less likely to experience symptoms than when free floating. Subjects with bilateral loss of labyrinthine function did not experience airsickness. The conclusion was reached that if weightlessness is a factor in precipitating symptoms of motion sickness in parabolic flight, it is not a strong factor.

None of the American astronauts and only Titov among the Russian cosmonauts experienced symptoms characteristic of vestibular sickness in orbital flight. If weightlessness was the significant factor causing Titov's symptoms, then vestibular sickness does pose a problem even if this was related to a greater than average susceptibility among a group of test pilots. If the problem exists, it might be lessened with more attention to selection and training, but this might be offset, in part at least, by the fact that, as spacecraft become larger, the freedom of movement of the astronauts will be greater, thus lessening their contact cues with the physical environment. Moreover, selection problems will be greater when astronauts are chosen from groups other than experienced pilots.

Weightlessness not only poses problems but also, insofar as it causes physiological deafferentation of the gravireceptors, it affords a unique and, in man, the only opportunity to carry out certain types of investigations. With the transition into weightlessness, the otolith organs are deafferented by a procedure which in an experimental laboratory would be termed elegant. This state of deafferentation will remain until movements of the head generate inertial forces above the threshold level; this need to avoid head movements which would generate an effective stimulus is a troublesome limitation. Simultaneous deafferentation of the nonotolith gravireceptors also acts as an experimental constraint. It is possible, however, to stimulate nonotolith gravireceptors to a limited degree without moving the subject's head and thus investigate the independent role of these receptors to perception of the upright and to space perception as revealed by egocentric visual localization of the "horizontal." We very much need to learn the independent roles of otolith and nonotolith factors and their complementary functions.

The inability adequately to simulate weightlessness under terrestrial conditions poses a problem in attempting to predict the susceptibility of an astronaut to functional disturbances of vestibular origin in weightlessness. One approach is based on the argument that, in the absence of stimulation to the semicircular canals, persons will experience motion sickness as a result of unusual patterns of afferent impulses in weightlessness constitutes one unusual pattern, and other patterns may be associated with movements of the head (body) in a weightless spacecraft.

The observations of Wendt (19-23) and others (24) that motion sickness is precipitated by exposure to rectilinear accelerations which do not stimulate the canals supports this argument without, however, specifically ascribing the motion sickness to the otoliths. Some observations of Graybiel and Johnson (25) utilizing a counterrotating room extended Wendt's observations in one regard, namely, that persons who had lost all or nearly all of the function of the otolith apparatus failed to experience motion sickness while normal subjects manifested varying degrees of susceptibility. In other words, stimulation of nonotolith gravireceptors was an inadequate precipitating factor although the subjects with labyrinthine and hearing loss experienced very much the same postural illusions as did the normal subjects. While this experiment failed to take into account the role of past conditioning and the possible role of the "presence of the canals," it offers the opportunity to compare the findings in such an environment with the findings in weightlessness. Final validation must of course await experience and experimentation aloft.

Additional experiments in weightlessness which should be carried out include: 1) the effect of deafferentation on the resting potential of the receptors in the macula and sacculus; 2) the effect of the resting discharge, if present, on such indicators as muscle tonus and ocular stability; 3) the relation between subgravity level and otolith function as revealed by counterrolling (26) or other indicator mechanisms under static and dynamic conditions; 4) the effects of prolonged deafferentation on the sensory receptors in animals as revealed by microscopy and on the function of the otoliths in man as revealed by a specific indicator, and 5) the effects of deafferentation on the functional organization of the central nervous system as revealed either by specific neurovegetative phenomena or their secondary effects.

Weightlessness also provides an opportunity to carry out investigations on the semicircular canals. We would like to know the effect of deafferentation of the otoliths on 1) the resting discharge of the sensory receptors in the crista, 2) the stimulus thresholds to angular and Coriolis accelerations and thermal stimulation, and 3) the susceptibility to illusory and other functional disturbances having their genesis mainly in the semicircular canals. A few such studies have been reported (9, 27-32), and it is an area under active investigation.

ARTIFICIAL GRAVITY

The question whether astronauts can tolerate exposure to weightlessness over long periods of time has not been answered and, in the absence of sufficient factual information, it has given rise to speculation and controversy. A weightless environment at best will prove wearisome and messy in carrying out ordinary activities of life and may, despite countermeasures, lead to unacceptable loss of fitness. Russian scientists (33) have stated that, in the light of their experimental findings, exposing man to weightlessness for more than one week may not be without risk and that an upper limit of two weeks would represent a reasonable increment above previous exposure periods. The incremental approach with man will provide the factual information needed to determine whether significant functional disturbances appear, and very long exposure periods for animals will provide additional information on alterations of both a functional and pathological nature. Meanwhile, in the event artificial gravity is needed, experiments are underway to determine how much artificial gravity is necessary to preserve fitness and, if this is accomplished by rotating the spacecraft, what countermeasures are needed to prevent the unwanted side effects. We will here confine our attention to the latter problem inasmuch as these side effects not only are a limiting factor in the design of rotating spacecraft but also these side effects have their genesis mainly in the semicircular canals.

In a rotating environment movement of the head in any direction or about any axis not parallel to the axis of rotation will generate, respectively, Coriolis and gyroscopic accelerations. The latter produces a gyroscopic torque which, through cross-coupling, is an effective but unusual stimulus to the semicircular canals. The bizarre nature of this stimulus may cause visual and postural illusions and if the stimulus is sufficiently strong or the person sufficiently susceptible, severe functional disturbances. How much of the disorder is due to the stimulus per se and how much to other associated factors is not easily determined, but the essentiality of the canals for nearly all of the disturbances is readily shown. For this reason the term canal sickness has been proposed as a convenient means of distinguishing this type of motion sickness.

The otolith organs, and nonotolith gravireceptors as well, are stimulated by the vector sum of gravitational, centripetal, and Coriolis forces. Near the axis of rotation the last two forces are small, but at increasing radii, for the same angular velocity, they become increasingly great. The changing values with bodily movements and at different positions with reference to the force environment will have a significant influence independently of the effects on the semicircular canals (34,35), but this influence is relatively small.

There are important differences between the force environment in a rotating spacecraft in orbital flight and a rotating room on earth, and certain effects of these differences are exaggerated as a result of man's orientation in the gravito-inertial force environment. Aloft, the artificial gravity will be generated by rotation of the spacecraft and represented by the centripetal force with the vector at right angles to the axis of rotation. The magnitude of the force will, in all likelihood, be less than 1.0 G unit,at least in the "first-generation" spacecraft. Thus, the astronaut will live in a subgravity force environment, and his natural position, with respect to the gravitoinertial upright, will be at right angles to the axis of rotation with head toward the center. With a short radius of rotation there would be a significant gradient in level of force between head and foot, and bodily movements along a radius not only would change the level of centripetal force but also might generate a significant Coriolis force. At relatively long radii and correspondingly slower angular velocities, changes in centripetal and Coriolis force would have rather small significance, but walking clockwise or counterclockwise might affect significantly the effective angular velocity. On rotating the head in <u>any</u> direction while upright, the astronaut would generate a gyroscopic acceleration causing the canals to be stimulated in an unusual manner; only if he rotated his head about the long axis of his body while lying parallel to the axis of the spacecraft would he avoid the unusual stimulus to the canals.

In the laboratory the subject in a rotating room lives in a supergravity environment, and the direction of the gravitoinertial vertical is mainly determined by the direction of gravity unless undesirably large centripetal forces are generated. Near the center of rotation his natural position is nearly upright. When the subject's head is parallel to the axis of rotation and he rotates his head about the long axis of his body, gyroscopic accelerations are <u>not</u> generated; they will be generated of course if the head is rotated about any other axis. To simulate more closely conditions aloft the subject should be constrained to "live and work" while supported on air bearings near the center of rotation.

A number of studies (36-38) have been reported in which subjects have been exposed in a rotating environment under different conditions and for periods varying from minutes to days at velocities varying from 1.0 to 10.0 RPM.

At a constant angular velocity, the experimental subject may not perceive that he is rotating. The room appears to be stationary and the walls upright. On moving the head normal subjects experience symptoms, the severity of which is a function of the angular velocity of the room, other factors remaining the same. One is struck with the disparity between the small magnitude of the forces and the great severity of symptoms which the subject may experience. Seated near the center of the room, he is scarcely aware of the small centripetal force and with the head fixed, he is comfortable.

Very briefly I will summarize some of the results of our investigations which have been carried out by a number of investigators working in our laboratory. These fall into two categories, brief exposures in the Slow Rotation Room (SRR) to estimate susceptibility to illusions and canal sickness and prolonged exposure to study summation and adaptation effects.

Brief Exposures. Systematic observations have been made on normal subjects either for the purpose of measuring susceptibility to canal sickness or for the study of more specifically evoked responses. With regard to the former, a so-called dial test (39) is used to standardize the stress to which a subject is exposed. Five dials are so placed in relation to the subject that, to set the needle at a given number on each dial, he is required to move his head and trunk to five different extreme positions which maximizes the gyroscopic stimulus to the canals. A sequence consists in setting the five dials, one every six seconds, followed by a six-second rest period. The initial velocity of rotation is 7.5 RPM, and the subject continues the task until either definite symptoms appear or until 20 sequences or 100 settings have been made. Then if 7.5 RPM is too stressful, the velocity is reduced, or if too weak, the velocity may be increased stepwise up to 20 RPM. With rare exceptions, normal persons experience definite symptoms at some velocity between 5.0 and 20.0 RPM. There is, usually, a progressive increase in number and severity of symptoms in the perrotation period, but exceptionally an initial increase is followed by a decline or even a disappearance, indicating coexisting effects of temporal summation and adaptation. Following cessation of rotation, symptoms in the majority of subjects disappear within a short time. In a randomly selected group of subjects a large majority will experience the typical symptoms of motion sickness including the nausea syndrome, drowsiness, pallor, and cold sweating. In some, the symptoms are more characteristic of anxiety or psychoneurosis and are further characterized by a discrepancy between the subjective and objective symptomatology.

Susceptibility to motion sickness as measured by the dial test is a fairly good prediction of susceptibility to symptoms in other force environments and to prolonged exposure in the SRR. The dial test is being used in the evaluation of anti-motion sickness drugs. The procedure utilizes the double blind technique, the introduction of placebos at intervals to determine shifts in baseline susceptibility as a result of habituation, and a symmetric matrix for convenience in statistical analysis. These studies are being carried out under the direction of Professor Wood, and his reports will soon be available. It would appear that the procedure has quite good reliability, but its validity in terms of application to other force environments remains to be determined. Inasmuch as susceptibility in the SRR is a fairly good predictor of susceptibility to symptoms in different force environments explored thus far, there is a reasonable expectation that we have a useful procedure for the evaluation of anti-motion sickness drugs under laboratory conditions, including good control of strength of the gyroscopic stimulus.

A number of subjects have been tested with varying degrees of loss of function of the sensory organs of the inner ears. In a group of deaf subjects with bilateral decrease or loss of canal function and either partial or complete loss of otolith function, none manifested symptoms of motion sickness. Four subjects with a history of successful treatment of Meniere's disease with streptomycin sulphate ten years previously did not experience symptoms of canal sickness. All had slight to moderate loss of canal function in one or both ears, but the function of the otoliths as revealed by the counterrolling test was within normal limits in one, slightly decreased in one, and moderately decreased in the other two. Even more revealing were the observations in a few subjects with normal hearing and otolith function but slight decrease in canal function who were either insusceptible to canal sickness or experienced minimal symptoms. At present, we are trying to establish what level of loss of canal function affords protection in the SRR and whether this same degree of protection is observed in other force environments, especially those in which the canals are not stimulated.

It is convenient at this place to mention briefly the results of experiments on squirrel monkeys selected on the basis of high susceptibility to canal sickness. Doctors Johnson and Money, collaborators from the Canadian Defence Research Laboratories, have found that, in squirrel monkeys, unilateral destruction of the labyrinth abolishes canal sickness only temporarily but that occluding two ducts bilaterally abolishes all sickness permanently. At the suggestion of Professor Schuknecht we have attempted to abolish canal sickness by administering streptomycin sulphate. Dr. McLeod has found that there is only a small range of dosage between ineffectiveness, at one extreme, and complete loss of function at the other. Within this range we have succeeded in raising the threshold to caloric stimulation temporarily during which period susceptibility to sickness was decreased or abolished. It is especially noteworthy that ataxia was absent during this period in some of the animals.

Prolonged Exposure. Prolonged rotation in the SRR affords the opportunity of studying the complete symptomatology experienced by subjects both during and after rotation and the effects of these symptoms on their performance.

In general, the higher the RPM, the more severe the symptoms and the slower the adaptation if individual susceptibility is taken into account. Many additional but mostly minor factors must be considered, however. At 1.0 RPM even highly susceptible subjects were symptom free, or nearly so. At 3.0 RPM subjects of average susceptibility were not significantly handicapped. At 5.4 RPM subjects with low susceptibility performed well and by the second day were almost free from symptoms. The only subject who did not adapt satisfactorily complained of symptoms characteristic of psychoneurosis. At 10 RPM, however, adaptation presents a challenging but interesting problem (38). Even pilots without a history of air sickness have not fully adapted in a period of twelve days. Initially, they were forced to restrict their head movements to prevent severe nausea. After a few days they no longer experienced nausea and, consequently, no longer restricted their head movements. They continued to complain of drowsiness and fatigue, however, and biochemical measurements revealed an increase in the release of corticosteriods, a striking increase in glucose utilization, and an increase in the plasma level of the enzyme lactic dehydrogenase. Even highly motivated and relatively insusceptible subjects were not fully adapted after the twelve days. Following the cessation of rotation the subjects simultaneously experienced a return of former symptoms and a decline in the residual symptoms. The lifelong habituation to the stationary environment was evident both in the mildness of the recurrent symptoms and in their short duration.

These few remarks on the general symptomatology associated with exposure to a rotating environment fail to do justice either to the many observations which have been made by ourselves and others or to the more specific investigations they have inspired. Suffice it here to say that much more experimentation is required. From the operational standpoint we need to fill out the tolerance profile for unprotected subjects with varying susceptibility to full adaptation at twenty different velocities. We need to investigate the effect of many countermeasures, unfavorable physiological or environmental factors, and the possibility of maintaining simultaneously adaptation to the rotatory and stationary environment. We need to simulate more closely conditions in a rotating spacecraft by keeping the subjects at right angles to the axis of rotation and learn how this compares with adaptation when the subjects are parallel to this axis. We need to explore fully the susceptibility to canal sickness as a function of rising threshold of canal function and, if possible, learn to bring about this state in a safe and reliable manner.

In conclusion I should like to emphasize the impact aviation and space medicine has had in stimulating interest in the semicircular canals and otolith organs. In the course of dealing with the applied aspects of the problems, gaps in our background knowledge of the functioning of these organs are being filled, and new procedures are being devised which will be useful to the clinical otolaryngologist and to those who wish to investigate, under controlled conditions, the influences of the canals and otoliths on central nervous system mechanisms. These last may prove to be of fundamental importance inasmuch as they bear on general adaptation processes and homeostatic mechanisms. It is hardly an exaggeration to state that when the mechanisms underlying the influences of the canals and otoliths are fully elucidated, it will constitute a sizable and significant contribution to an understanding of man.

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